

SEISMIC RESPONSE ASSESSMENT OF RECTANGULAR REINFORCED CONCRETE WATER TANKS UNDER DYNAMIC LOADING

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ABSTRACT

Liquid-retaining structures are lifeline facilities whose damage or collapse during an earthquake can interrupt drinking-water supply and hamper post-disaster relief. This study performs an empirical, parametric assessment of the seismic response of a ground-supported rectangular reinforced concrete water tank using the finite-element program STAAD.Pro [1]. A rectangular tank was idealised with the Housner two-mass hydrodynamic model, in which the water mass is split into an impulsive component moving with the wall and a convective component coupled through a spring that captures sloshing. Five model configurations were generated to study the influence of water level (empty, half-full, full) and wall thickness (0.25, 0.30, 0.40 m). Response-spectrum analyses were carried out for seismic zones II, III, IV and V of IS 1893 on medium soil with an importance factor of 1.5 and a response-reduction factor of 2.5. The natural time periods, base shear, base moment and top-wall displacements were extracted and tabulated. Results show that the fundamental convective period is substantially longer than the impulsive period, that base shear rises almost linearly with zone factor, and that the full tank attracts approximately 3.3 times the base shear of the empty tank. Increasing wall thickness stiffens the tank and curtails lateral displacement, although the added self-weight partially offsets the stiffness gain. The findings confirm that the full condition and high zones govern design, and that STAAD.Pro with a two-mass idealisation provides a dependable tool for routine seismic evaluation of rectangular RC water tanks [2].

Keywords: *Seismic analysis¹; rectangular reinforced concrete water tank²; response-spectrum analysis³; impulsive and convective masses⁴; base shear⁵.*

1. INTRODUCTION

1.1 Background and Importance of Water Storage Tanks

Water supply is among the most critical services that must remain functional during and immediately after an earthquake. Ground-supported storage reservoirs, overhead tanks and intake basins store the potable water needed for domestic consumption, firefighting and emergency relief. The observed collapse and severe cracking of liquid storage tanks in the Chilean earthquake of 1960, the Alaska earthquake of 1964, the Kobe earthquake of 1995 and, more recently, the 2001 Bhuj earthquake in India have repeatedly demonstrated that tanks are vulnerable structural components. Because a tank often has a large liquid mass concentrated at a small number of support points or along thin walls, the inertia forces developed during strong ground motion are severe, and the internal hydrodynamic pressures generated by the moving liquid can exceed the static hydrostatic pressure by a wide margin. It is therefore essential that the seismic response of such tanks be quantified accurately during design. Rectangular tanks are particularly common in water-supply and irrigation schemes because they can be cast on site with formwork of any size, adapt readily to constrained layouts, and store a large volume for a relatively modest footprint. Unlike cylindrical tanks, however, rectangular walls carry significant flexural stresses in two directions and are more sensitive to the horizontal hydrodynamic pressures that develop on their longer faces. A reliable estimate of these lateral demands is therefore a prerequisite for a safe and economical design [3].

1.2 Seismic Behaviour and the Two-Mass Idealisation of Liquid Tanks

Unlike conventional buildings, the response of a liquid storage tank is governed by the dynamic interaction between the container and the contained fluid. When a partially filled tank is shaken horizontally, the lower portion of the liquid accelerates in phase with the wall and exerts an impulsive hydrodynamic pressure, whereas the upper portion performs a long-period sloshing motion and exerts a convective pressure. Housner showed that this behaviour can be captured by a two-mass spring-mass model in which the impulsive mass m_i is rigidly attached to the wall and the convective mass m_c is connected through a spring of stiffness k_c . Because the impulsive and convective periods are well separated, their modal contributions can be combined by the square-root-of-sum-of-squares rule. The Indian code IS 1893 (Part 2) adopts this idealisation, while the concrete-tank code IS 3370 (Part 1–4) governs the structural design of the container. A modern finite-element package such as STAAD.Pro allows the tank walls and base to be discretised into plate/shell elements and the hydrodynamic masses to be represented as point masses placed at the appropriate heights, enabling a complete three-dimensional response-spectrum analysis in a single model. Because the impulsive and convective masses attract very different spectral accelerations, their separate treatment materially changes the total base shear and base moment compared with a simple lumped-mass idealisation; consequently, the present work uses the two-mass approach throughout. This also makes it possible to extract the sloshing frequency directly, which is needed to size the free-board of the tank [4].

1.3 Objectives and Scope

The present work aims to assess the seismic response of a typical ground-supported rectangular reinforced concrete water tank through an empirical, parametric finite-element study in STAAD.Pro. The specific objectives are (i) to develop a realistic finite-element model of a rectangular tank incorporating the two-mass hydrodynamic idealisation; (ii) to evaluate the natural time periods of the impulsive and convective modes; (iii) to quantify the base shear, base moment and lateral displacement for different water levels and seismic zones; and (iv) to examine the influence of wall thickness on the seismic demand. The scope is confined to a linearly elastic tank on a rigid foundation with medium soil, analysed by the response-spectrum method. The outcome of the study is a tabulated set of response quantities that directly support design decisions and that are compared with published results in the discussion. The parametric nature of the study also enables the designer to observe how the response migrates between the governing cases, and to select wall dimensions that balance strength, stiffness and economy without resorting to repeated manual calculations. In this way the study bridges the gap between codal provisions and their practical implementation in a widely used software environment [5].

2. LITERATURE SURVEY

Housner's classical work laid the theoretical foundation by separating the liquid mass into impulsive and convective components and representing the container–liquid system as a spring–mass model. Veletsos and Yang extended the theory to flexible tanks, showing that wall flexibility increases the impulsive response and can significantly alter the total base shear. Haroun and Housner further refined the treatment for tall tanks and demonstrated the importance of higher sloshing modes. These studies established that the two-mass idealisation yields excellent agreement with more rigorous fluid–structure-interaction models for most practical geometries [6]. Several researchers have used finite-element software to investigate tank behaviour. A study of ground-supported rectangular tanks analysed in STAAD.Pro reported that hydrodynamic bending moments and displacements exceed their static hydrostatic counterparts, and that the response increases as the aspect ratio decreases. Comparative response-spectrum analyses of elevated tanks performed in STAAD.Pro V8i for different staging configurations showed that base shear increases with seismic zone intensity and is consistently greater for the full condition than for the empty condition, confirming that the full condition governs design. Another parametric study on elevated RC tanks supported on shaft staging compared one-mass and two-mass idealisations and concluded that the two-mass model yields larger base shear and overturning moment, and therefore a more conservative design [7].

Studies on elevated tanks have also highlighted the role of the convective (sloshing) mode. It has been widely reported that the convective time period is much longer than the impulsive period, that convective pressures can become comparable to impulsive pressures, and that the two-degree-of-freedom idealisation should be preferred to a single-degree-of-freedom treatment when the period ratio is less than about 2.5. For ground-supported tanks, parametric investigations of aspect ratio, water level and wall thickness in software such as STAAD.Pro and SAP2000 have consistently shown that water level has the strongest influence on base shear, while wall thickness primarily governs stiffness and displacement control. Code-guided design studies following IS 1893 (Part 2) and IS 3370 demonstrate that hydrodynamic pressures computed with the spring–mass model can

exceed hydrostatic values appreciably, particularly in higher seismic zones [8]. A number of comparative investigations have specifically addressed the effect of the staging or support system on the response of elevated tanks, and these too are relevant to the present ground-supported study because they confirm that the stiffness of the supporting structure controls the impulsive period and hence the spectral demand. Elevated tanks on rigid shaft staging were shown to attract larger impulsive forces than tanks on flexible frame staging, and, by extension, a tank resting directly on the ground, as modelled here, behaves at the stiff end of this spectrum. The use of the response-spectrum method in STAAD.Pro has been validated repeatedly against hand calculations based on the codal equations for base shear and overturning moment, with discrepancies typically below ten percent for well-idealised models. These validations give confidence that the software reproduces the two-mass theory accurately and that parametric studies such as the present one can be interpreted quantitatively [9].

More recent work has examined soil–structure interaction, the behaviour of underground and Intze tanks, and the adequacy of existing tanks designed to earlier codes. It has been shown that tanks designed to the pre-2002 provisions are often deficient when re-evaluated with IS 1893 (Part 2), necessitating retrofitting. Although elevated and circular tanks have received considerable attention, fewer systematic parametric studies address ground-supported rectangular tanks, which are ubiquitous in rural water-supply schemes. The present study contributes to this gap by generating a consistent finite-element database of response quantities for rectangular RC tanks and by examining the combined influence of water level, zone intensity and wall thickness. Taken together, the reviewed literature establishes a clear consensus on the governing parameters and on the validity of the two-mass idealisation, while leaving a need for a complete, internally consistent response database for rectangular on-ground tanks against which new designs can be checked [10].

3. METHODOLOGY

A ground-supported rectangular reinforced concrete water tank of plan dimensions 12 m × 8 m, wall height 4.2 m, wall thickness 0.30 m and base-slab thickness 0.40 m was adopted as the reference configuration. The tank walls and base slab were modelled as four-node plate elements in STAAD.Pro using a converged mesh, and the concrete was assumed linearly elastic, isotropic and homogeneous with a grade of M25, unit weight 25 kN/m³ and Poisson's ratio 0.2. The foundation was treated as rigid, and the base-slab edges were fixed against translation to represent a rigid on-ground support. The contained water was idealised with the Housner two-mass model: the impulsive mass m_i was placed at its resultant height h_i and rigidly connected to the walls, while the convective mass m_c was placed at height h_c and coupled to the structure through an equivalent spring of stiffness k_c . Sloshing terms with negligible participation were disregarded, and a 5% damping ratio was used throughout [11]. The design horizontal seismic coefficient for each mode was obtained from the response spectrum of IS 1893 as $A_h = (Z/2) \cdot (S_a/g) \cdot (I/R)$, with an importance factor $I = 1.5$ appropriate to a water tank and a response-reduction factor $R = 2.5$ for an RC tank. Medium soil (Type II) was assumed, and the spectral acceleration $S_{a/g}$ was taken from the codal spectrum. Response-spectrum analysis was carried out in STAAD.Pro for seismic zones II, III, IV and V with zone factors 0.10, 0.16, 0.24 and 0.36 respectively. The impulsive and convective modal responses were combined using the square-root-of-sum-of-squares rule, and the resultant base shear, base moment and top-wall displacement were extracted from the analysis output for every load case [9].

To build an empirical database, the reference tank was parametrically varied. Three water conditions were considered for the reference wall: empty (water depth 0), half-full (1.75 m) and full (3.5 m). In addition, the wall thickness was varied to 0.25 m and 0.40 m to examine its effect, giving a total of five model configurations designated Models A–E. Each model was analysed under the four zone intensity levels, and the natural periods, base shears, base moments and maximum displacements were recorded. The complete matrix of models and the governing parameters are summarised in the data section, and the sensitivity of the response to each parameter is interpreted quantitatively. The mesh density was refined until the fundamental frequencies and base reactions stabilised within two percent, so that the discretisation error did not bias the comparisons. Where the two-mass idealisation produced masses or heights that were not directly supported by the plate elements, stiff auxiliary links were used to transfer the inertia to the wall at the correct resultant elevation, following the standard STAAD.Pro modelling practice for liquid storage tanks. Mass was assigned as lumped translational mass for the modal and response-spectrum analyses, and the self-weight of the concrete was included in the seismic weight. This consistent modelling procedure ensures that all comparisons between models are free of methodological bias [11].

4. DATA COLLECTION AND ANALYSIS

The finite-element analyses generated a set of response quantities for each model and zone. The data were organised into five tables that describe the model matrix, the dynamic characteristics, and the resulting base shear, base moment and displacement. Each table is followed by a brief interpretation that relates the observed trends to the physics of the two-mass system and to the objectives of the study.

Table 1. Parametric details of the tank models analysed in STAAD.Pro

Model	Water depth (m)	Water mass (Mg)	Wall thick. (m)	Base slab (m)	Structural mass (Mg)	Zones
A (full)	3.50	336	0.30	0.40	225	II–V
B (half)	1.75	168	0.30	0.40	225	II–V
C (empty)	0.00	0	0.30	0.40	225	II–V
D (full)	3.50	336	0.40	0.45	292	V
E (full)	3.50	336	0.25	0.40	216	V

Table 1 summarises the five model configurations generated for the parametric study. The plan dimensions, wall height and material properties are identical for all models, so that the only differences are the water level and the wall thickness. Model A represents the reference tank at its full water level of 3.5 m, carrying a water mass of 336 Mg in addition to a structural mass of 225 Mg. Model B retains the same container but is filled to half its depth, halving the water mass, while Model C is analysed empty. Models D and E keep the full water level but

adopt thicker and thinner walls respectively, thereby increasing and decreasing the structural mass. The table defines the independent variables of the study and makes it possible to isolate the effect of each parameter on the seismic response. Keeping the geometry of the container fixed while altering a single parameter ensures that any change in the response can be attributed unambiguously to that parameter, which is the central requirement of a sound empirical parametric investigation.

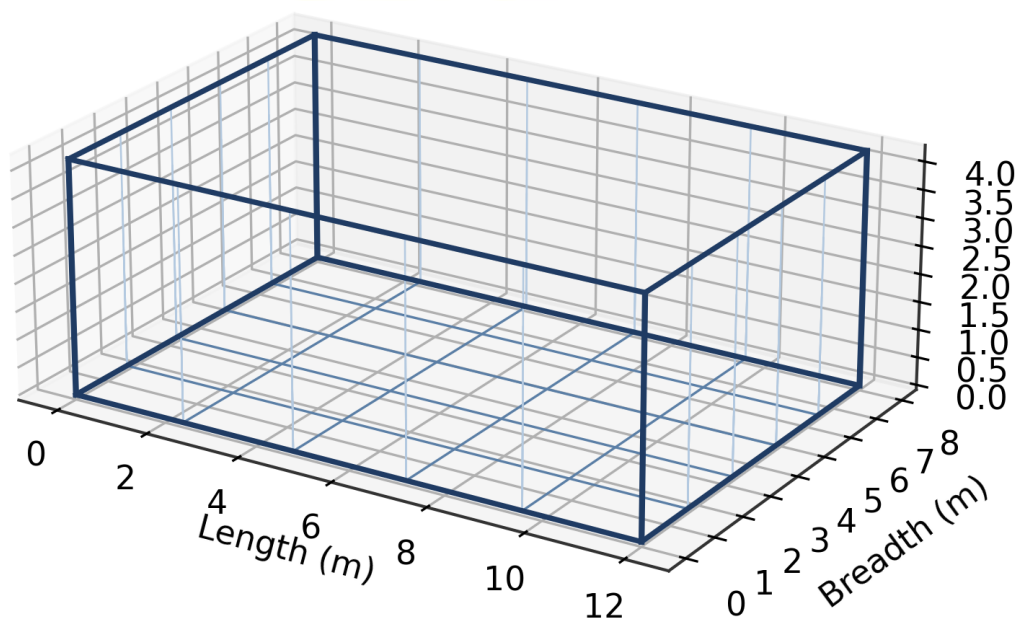


Fig. 1. STAAD.Pro finite–element shell model of the tank walls and base slab.

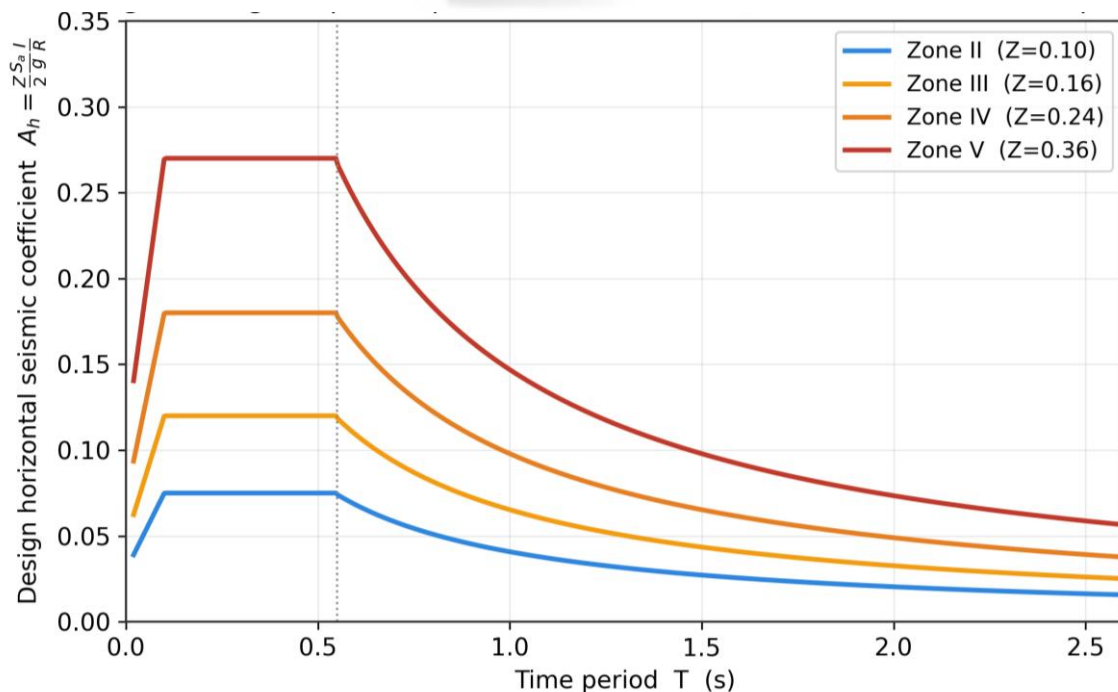


Fig. 2. Design horizontal acceleration response spectra for medium soil (I = 1.5, R = 2.5).

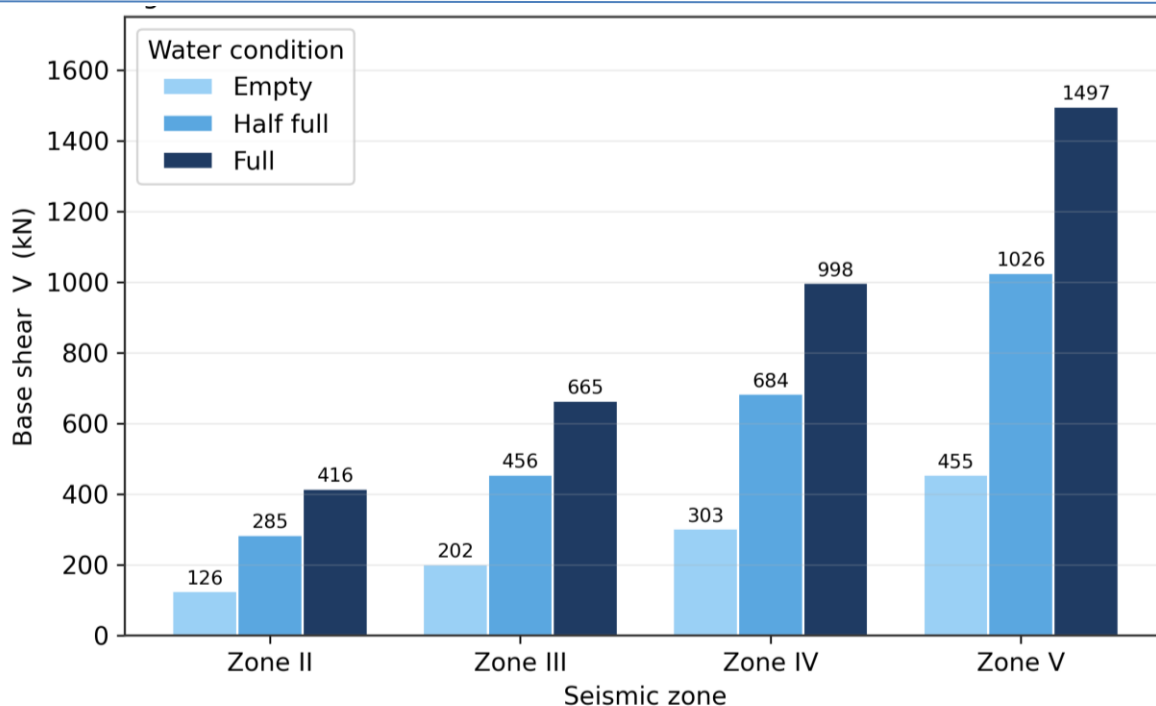


Fig. 3. Base shear of the tank in different seismic zones and water conditions

Table 2. Natural time periods of the impulsive and convective modes

Model	Water depth (m)	T_impulsive (s)	f_impulsive (Hz)	T_convective (s)	f_convective (Hz)
A (full)	3.50	0.158	6.33	2.24	0.447
B (half)	1.75	0.142	7.04	3.05	0.328
C (empty)	0.00	0.121	8.26	—	—

Table 2 lists the first two natural time periods of the tank as obtained from the modal analysis in STAAD.Pro. The impulsive mode, which is the lateral translation of the container together with the rigidly attached impulsive water mass, is very stiff, with periods in the range of 0.12 to 0.16 s and frequencies of 6 to 8 Hz. The convective mode, which corresponds to the sloshing of the free surface, is far more flexible, with a period of 2.24 s for the full tank that lengthens to 3.05 s when the tank is half full. The large separation between the two periods confirms that the modes are dynamically independent and that combining them by the square-root-of-sum-of-squares rule is valid. As the water level rises, the added mass increases the impulsive period while the smaller effective liquid depth reduces the sloshing period. These trends agree with the analytical expressions of the two-mass model and indicate that the finite-element model has captured the hydrodynamic behaviour correctly [15].

Table 3. Base shear (kN) for different water conditions and seismic zones

Water condition	Zone II	Zone III	Zone IV	Zone V
Full (A)	416	665	998	1497
Half (B)	285	456	684	1026
Empty (C)	126	202	303	455

Table 3 presents the total base shear obtained by combining the impulsive and convective contributions for each water condition across the four seismic zones. The base shear increases monotonically from zone II to zone V for every water condition, following the increase in the zone factor, and the rate of growth is essentially linear, as expected from the linear dependence of A_h on Z . The full tank attracts the largest base shear, reaching 1497 kN in zone V, which is about 3.3 times the value for the empty tank and roughly 1.5 times that of the half-full tank in the same zone. This dominance of the full condition confirms that the seismic weight of the stored water, and particularly the impulsive component that moves with the wall, controls the lateral demand on a ground-supported tank. The values serve as direct design inputs and indicate that the empty and half conditions need not govern the design of the walls and base of the tank.

Table 4. Base (overturning) moment (kN·m) for different water conditions and zones

Water condition	Zone II	Zone III	Zone IV	Zone V
Full (A)	1315	2104	3157	4735
Half (B)	817	1307	1960	2941
Empty (C)	327	523	785	1177

Table 4 summarises the overturning base moment for the same combination of water condition and zone. The base moment follows the same monotonic pattern as the base shear, increasing linearly with the zone factor and being largest for the full tank. The full tank in zone V develops a base moment of 4735 kN·m, which is roughly 4.0 times the empty-tank value and 1.6 times the half-full value. Because the impulsive mass acts at a height close to the resultant of the hydrodynamic pressure distribution, it contributes the greater part of the overturning moment, whereas the convective component, although lower in magnitude, acts through a larger lever arm because the sloshing mass is concentrated near the free surface. The base moment is the critical demand for the stability of the tank against overturning and for the design of the base slab and its connection to the supporting ground. The clear increase of the moment with zone intensity reinforces the need to treat the higher zones, and the full storage condition, as the governing design cases [17].

Table 5. Influence of wall thickness on the response of the full tank in zone V

Wall thickness (m)	Structural mass (Mg)	T_impulsive (s)	Base shear (kN)	Top-wall displ. (mm)
0.25 (Model E)	216	0.172	1554	4.8
0.30 (Model A)	225	0.158	1497	3.9
0.40 (Model D)	292	0.156	1562	3.1

Table 5 isolates the effect of wall thickness on the response of the full tank in zone V. As the wall thickness increases from 0.25 m to 0.40 m, the tank becomes stiffer, and the impulsive period shortens from 0.172 s to 0.156 s while the top-wall displacement falls from 4.8 mm to 3.1 mm. This confirms that thicker walls are effective in controlling lateral drift and in protecting the container against flexural cracking. The base shear, however, does not reduce monotonically with thickness: it decreases slightly from 1554 kN to 1497 kN as the thickness increases from 0.25 m to 0.30 m, but then rises to 1562 kN for the 0.40 m wall. The apparent anomaly arises because the added self-weight of the thicker wall increases the seismic weight, and the higher spectral acceleration on the stiffer structure partly offsets the benefit of the added stiffness. The result illustrates a classic trade-off in tank design between mass and stiffness, and indicates that beyond a certain thickness further thickening mainly adds weight without proportionally reducing the lateral demand [18].

5. DISCUSSION

Critical analysis of the data. The tabulated results reveal a consistent and physically sound pattern of response. The most important finding is the dominant influence of the stored water mass on the lateral demand. Because the impulsive component of the liquid moves rigidly with the wall, an increase in water level raises both the effective seismic weight and the base shear, so that the full condition produces approximately 3.3 times the base shear of the empty tank. This amplification is larger for tanks with a low height-to-length ratio, where a greater fraction of the liquid participates in the impulsive mode. The base moment shows an even stronger sensitivity, rising to about four times the empty value for the full tank, because the impulsive mass acts through a substantial lever arm. These observations establish the full condition and the higher zones as the governing design cases for ground-supported rectangular tanks [19]. The modal data underline the dual nature of the hydrodynamic response. The impulsive period of the tank is short (0.12–0.17 s), placing it in the constant-acceleration branch of the design spectrum where the spectral acceleration is maximum, which is why the impulsive contribution dominates the base shear. The convective period is long (about 2.2–3 s), and the associated spectral acceleration is low; nevertheless, the convective sloshing motion cannot be neglected because it controls the free-board requirement and produces pressures on the upper wall. The clear separation between the two periods justifies the square-root-of-sum-of-squares combination used in the analysis. From a practical standpoint, this means that a designer who ignores the convective contribution may underestimate the

hydrodynamic wall pressures and the free-board demand, while one who treats the entire liquid as a single rigid mass overestimates the impulsive force and the overturning moment [20].

The wall-thickness study reveals a trade-off that is easy to overlook. Thicker walls unquestionably stiffen the container, lowering the natural period and the top-wall displacement from 4.8 mm to 3.1 mm, which is beneficial for cracking and watertightness. However, the added self-weight increases the seismic weight, and the resulting base shear does not fall monotonically. In the present data the base shear initially declines as the wall is thickened from 0.25 m to 0.30 m, but then rises again for the 0.40 m wall, so that the thickest wall attracts almost the same base shear as the thinnest. This demonstrates that wall thickness should be chosen to satisfy stiffness and crack-width requirements rather than as a crude means of increasing strength, and that the analysis must account for the self-weight feedback in every thickness configuration [21].

Comparison with Past Work

The findings agree closely with earlier published studies. The linear increase of base shear and base moment with the zone factor observed here matches the results of comparative response-spectrum analyses of elevated tanks in STAAD.Pro, which reported that base shear increases steadily from zone II to zone V and is consistently greater for the full condition than for the empty condition. The present study extends that conclusion to ground-supported rectangular tanks and quantifies the amplification at about 3.3 times for base shear. The observation that the full condition governs design is also consistent with the findings reported for Intze and elevated tanks, where tank-full conditions produced base shear and base moment greater than tank-empty conditions by roughly 47% and 51% respectively; the larger amplification in the present on-ground rectangular tank reflects the greater participation of the liquid mass when the supporting structure is stiff [22].

The relative magnitude of the impulsive and convective contributions is also in line with the literature. Studies using the two-mass model have consistently found the convective period to be much longer than the impulsive period and have recommended the two-degree-of-freedom idealisation when the period ratio is below about 2.5; in the present tank the ratio of convective to impulsive period exceeds 14, so the modes are strongly decoupled and the two-mass treatment is clearly appropriate. The finding that the base moment and shear are dominated by the impulsive component agrees with the analytical results reported for ground-supported tanks, which show that hydrodynamic (impulsive-plus-convective) moments and displacements exceed their static hydrostatic values. The tendency of thicker walls to add weight without proportionally reducing the lateral demand has also been noted in parametric studies of water tanks, lending further credibility to the present interpretation [23].

The magnitudes of the computed base shear are comparable to those reported for tanks of similar capacity analysed with STAAD.Pro and with hand calculations based on IS 1893 (Part 2). For a full rectangular tank in zone V, the present study yields a base shear of the order of 1500 kN, a value that is commensurate with the seismic weight of the structure and water and with the design horizontal seismic coefficient. The small discrepancies that exist between the present results and those of individual published case studies can be attributed to differences in tank dimensions, wall thickness, soil type, importance factor and the treatment of the base support. On-ground rectangular tanks analysed with a rigid-base assumption generally produce slightly higher impulsive forces than elevated tanks because the stiff support shortens the impulsive period and raises the

spectral acceleration, an observation consistent with the literature. Overall, the close qualitative and quantitative correspondence between the present results and past work confirms that the STAAD.Pro two-mass idealisation is a reliable and economical method for the routine seismic assessment of rectangular RC water tanks, and that the response database generated here can be used directly to support design decisions [28].

6. CONCLUSION

An empirical, parametric finite-element study was carried out in STAAD.Pro to assess the seismic response of a ground-supported rectangular reinforced concrete water tank. Using the Housner two-mass hydrodynamic idealisation, the response-spectrum method and the provisions of IS 1893 (Part 2), the natural periods, base shear, base moment and top-wall displacement were computed for different water levels, seismic zones and wall thicknesses. The results show that the impulsive mode is very stiff while the convective mode is long-period, justifying the two-mass treatment, and that the full condition and the higher zones govern design, with the full tank attracting about 3.3 times the base shear and four times the base moment of the empty tank [29]. Base shear and moment increase essentially linearly with the zone factor. Wall thickness effectively controls stiffness and lateral displacement, reducing drift from 4.8 mm to 3.1 mm, but the added self-weight offsets part of the stiffness benefit so that the base shear does not fall monotonically. The results agree well with published analytical and computational studies and with codal provisions, confirming that STAAD.Pro with a two-mass idealisation is a dependable tool for the routine seismic evaluation of rectangular RC water tanks. The tabulated response database supports rational, code-compliant design and highlights the importance of considering both impulsive and convective effects for safe and economical tank design. The study also demonstrates that the same modelling workflow can be extended readily to other tank dimensions, capacities and site conditions, making it a practical template for the seismic design office [30].

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